

9-Ft by 7-Ft Supersonic Wind Tunnel Nozzle Improvement Study



Presented By Eric Paciano on behalf of NASA Ames Research Center
121st Supersonic Tunnel Association International Meeting

San Francisco, CA

Tuesday May 13th 2014

Note: This information is for use by STAI members only and is not to be referred to in print without the authors permission

JACOBS



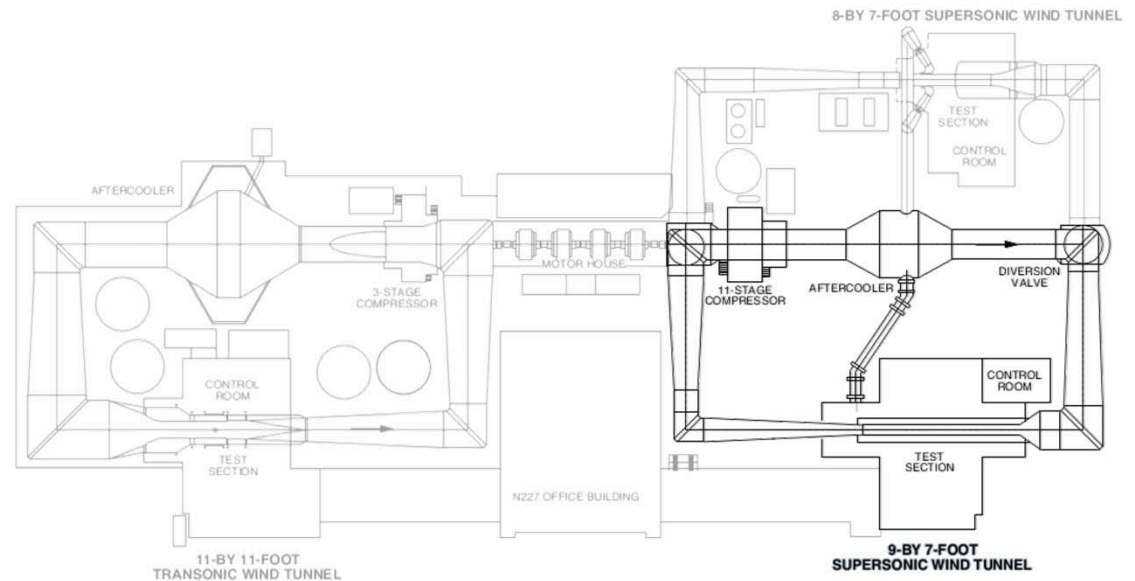
Agenda

- Background
 - Facility Description
 - Flow Characteristics
- Nozzle Improvement Study
 - Project Metrics
 - Methodology
 - Predictive Tools
 - Potential Solutions
- Current Status & Future Direction



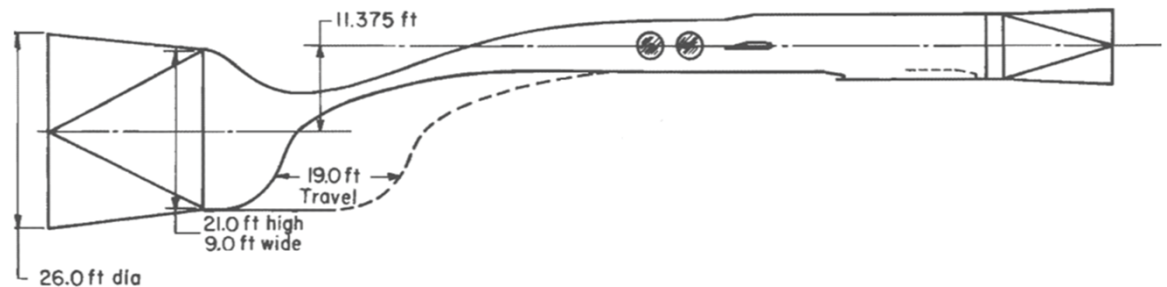
UPWT Facility Background

- Built in the 1950's to meet national aero testing demands
- Consists of 3 tunnels driven from a common motor set
 - 11-Ft Transonic ($M=0.2$ to 1.5)
 - 9-Ft by 7-Ft Supersonic ($M=1.5$ to 2.54)
 - 8-Ft by 7-Ft Supersonic ($M=2.5$ to 3.5) (*currently inactive*)
- Site also includes an Auxiliary Facility and MUA compressor



9x7 SWT Background

- 11-stage axial compressor
- 176-MW total power limit
- Horizontal model support strut
- Asymmetric sliding block nozzle



Characteristic	Unit	Min	Max
Mach Number	--	1.5	2.54
Reynolds Number	Millions/Ft	1.4	5.4
Dynamic Pressure	Psf	300	1170
Total Pressure	Psfa	630	3600

Asymmetric Nozzle

- Mach range of the 9x7 requires drastic throat area change
 - Prohibited flex wall implementation
- Plug-type nozzle explored as alternative
 - Wake and shocks generated by plug interfere with model
- Asymmetric nozzle is one-half of a two dimensional plug-type nozzle

Reference: Allen, H., "The Asymmetric Adjustable Supersonic Nozzle For Wind Tunnel Application", NACA TN-2919

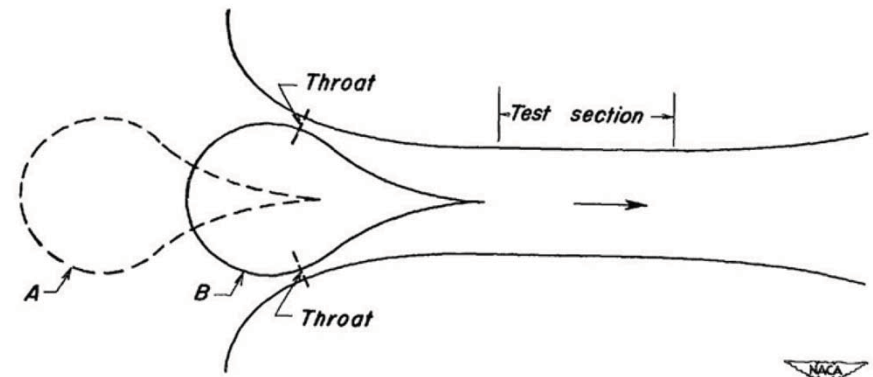


Figure 5.— Silverstein plug-type supersonic nozzle.

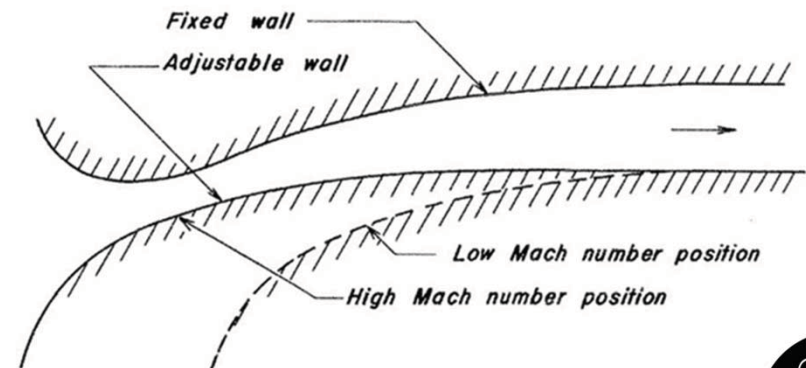
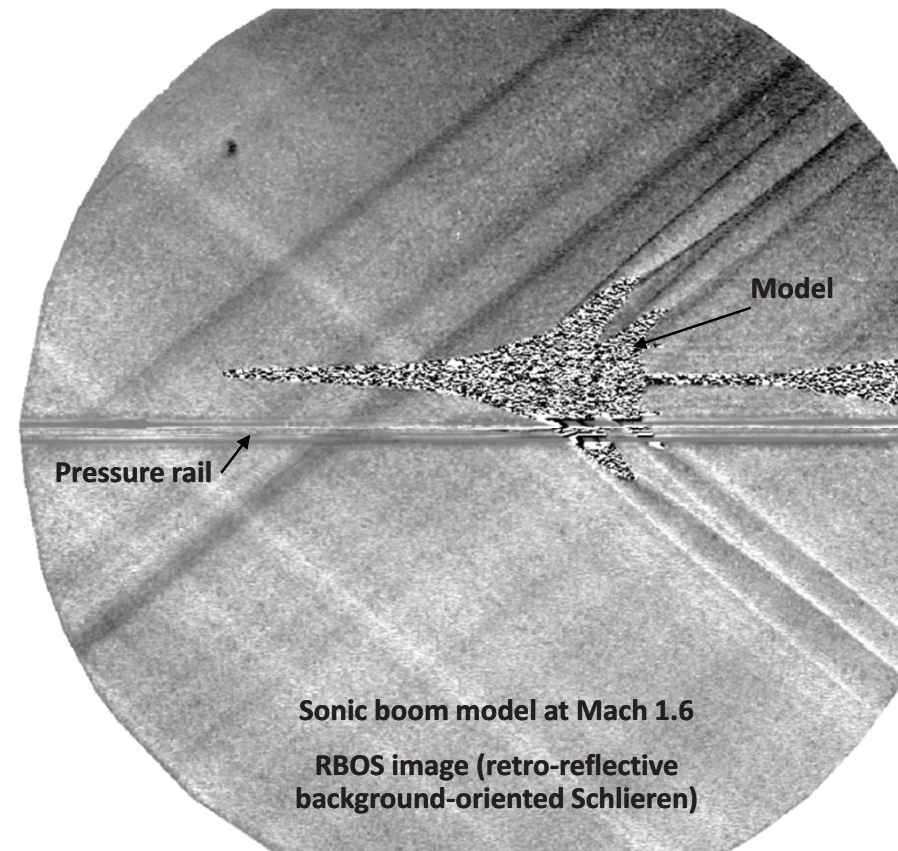


Figure 7.— Asymmetric adjustable supersonic nozzle.

Recent Sonic Boom Testing Concerns

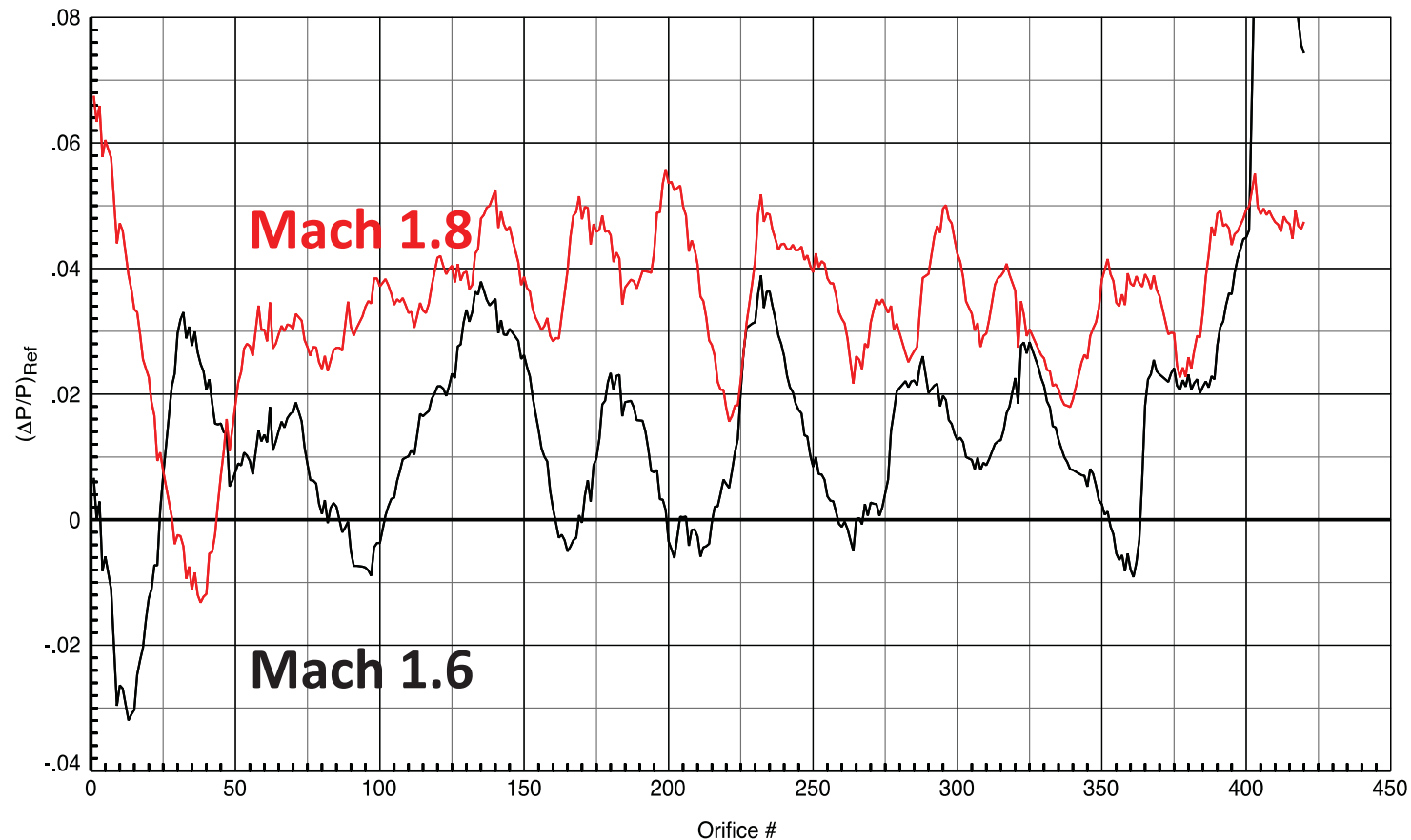
Problems with measurements of sonic boom pressure signatures are due mostly to wind tunnel temporal and spatial variations being *greater* than the pressure increments we're trying to measure

- Stray background shocks often stronger than model shocks, mask model pressure signature
- Test section static pressure unsteadiness and spatial variation should be reduced
- Flow angularity variation throughout test section should be reduced



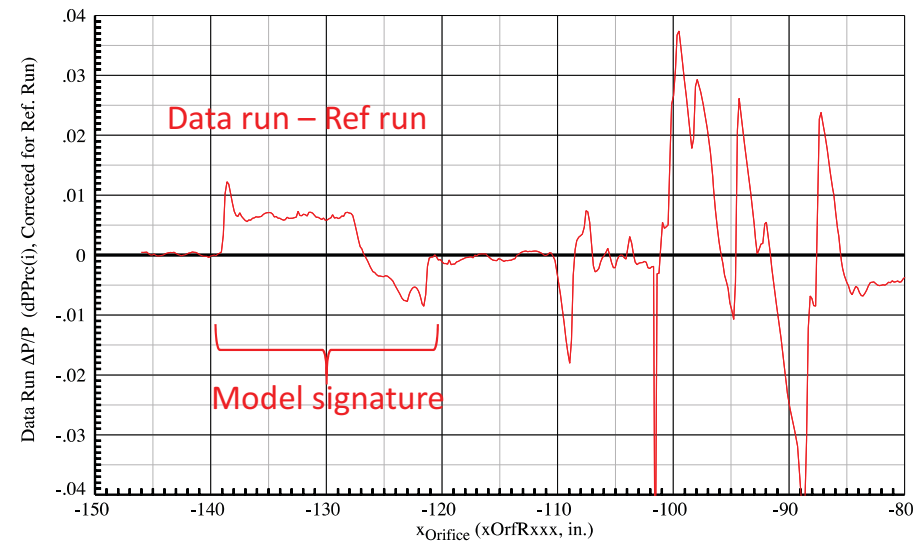
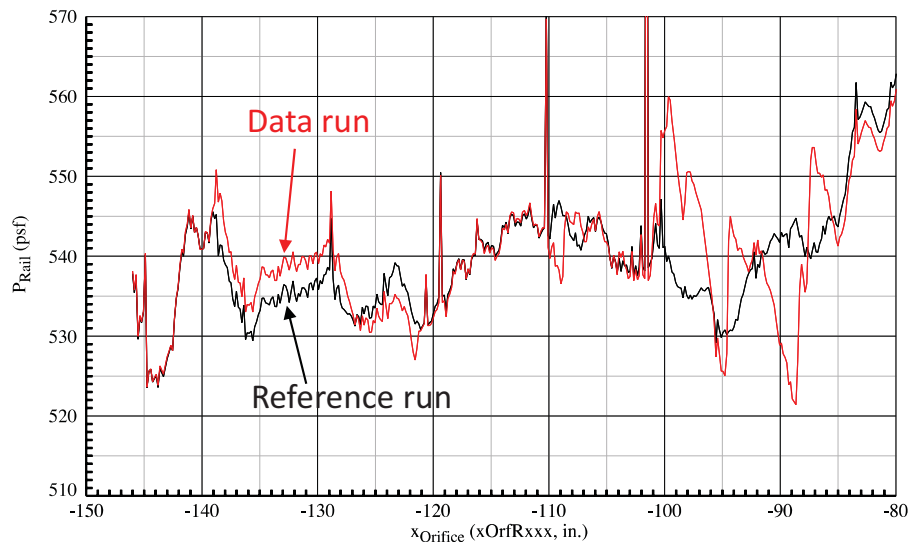
Empty-Tunnel Static Pressure Variations

Some variation along rail is expected, but many compressions and expansions are evident in the flow throughout the test section



Sonic Boom Model Pressure Signature Data

- Model signature increments are small relative to empty-tunnel pressure variations
- Tunnel flow unsteadiness makes model signature measurements even more difficult



Mach 1.6, $P_T = 2300$ psf

Improvement Project Scope & Metrics

Perform a study of the 9x7 nozzle and test section to:

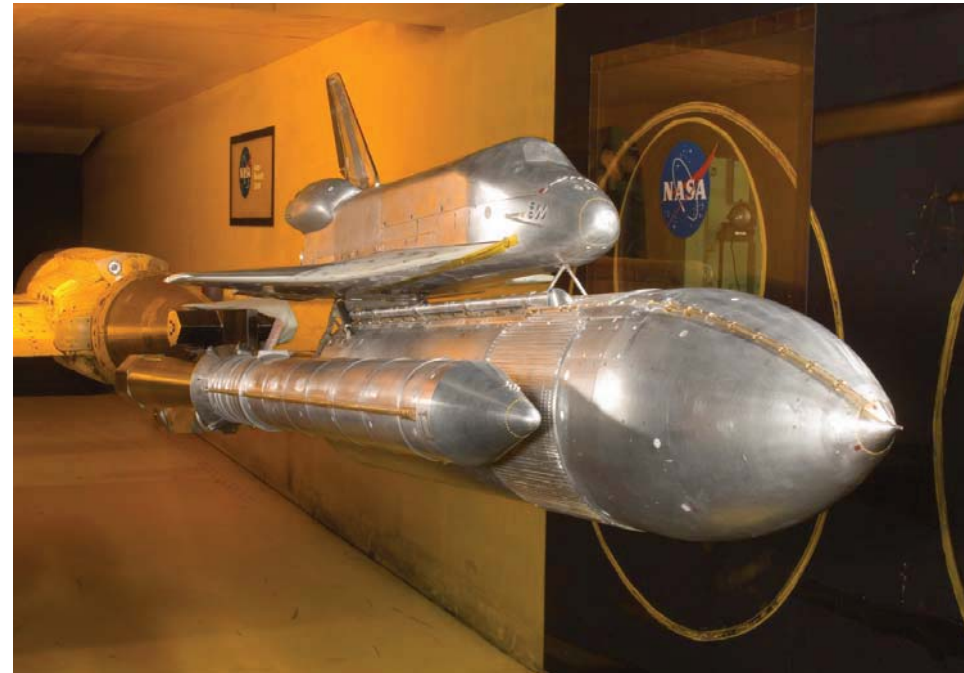
- Create a CFD model that accurately predicts the 9x7 nozzle and test section flow
- Identify the cause and source of the Mach number and pressure variations
- Refine the model based on survey data to match actual tunnel data
- Use the model to analyze and evaluate various flow improvement concepts

Flow Quality Metrics:

Location	Measurement	Value	Range
Test Section Streamwise Centerline	Mach # Variance	0.1% Max	Station 80 to 180
North Wall to South Wall	Mach # Variance	0.25% Max	Station 80 to 180 Z = +24 to -24 (in)
Floor to Ceiling	Mach # Variance	0.25% Max	Station 80 to 180 Y = +24 to -24 (in)

Solution Methodology

- Define Tunnel Geometry
 - 2D Construction-era drawing set
 - 3D Scan data
- Determine appropriate numerical solver by comparison to calibration data
 - Method of Characteristics
 - JUSTUS
 - Euler Module
- Explore alternate nozzle curvature at Mach 1.6 with the goal of achieving uniform flow in the test section
 - Evvard & Marcus
 - Upstream Marching
 - Heuristic
- Develop flow field predictions using the alternate curvature throughout Mach range



Geometry Definition: 3D Scan

- Large format 3D laser scanner coupled with laser tracker
- Data acquired:
 - From test section and settling chamber
 - For Mach setting 1.3 to 2.5 at 0.1 increments
 - With multiple repeats
- Scan performed by Automated Precision Incorporated

API SERVICES

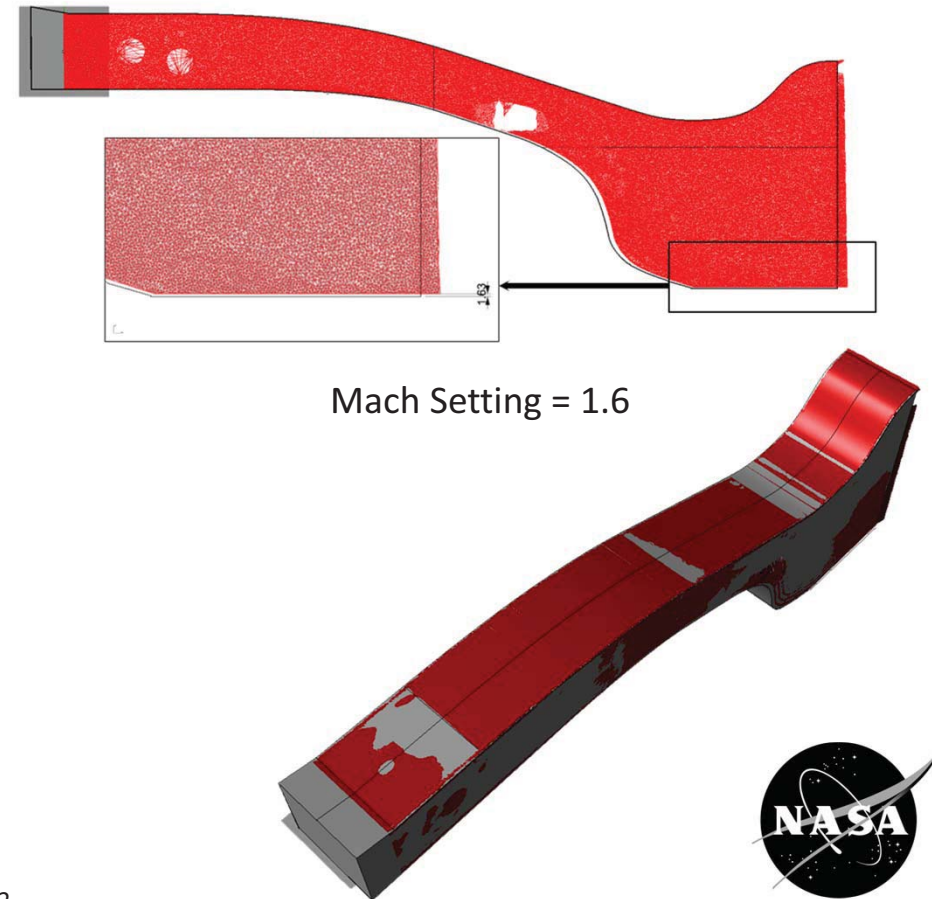


JACOBS™



3D Scan / 2D Drawing Deviation

- Preliminary analysis was conducted using a geometry based on the 2D drawing set
- Comparisons between 3D scan data and geometry showed a vertical offset of 1.63-in
 - Likely caused by incorrect nozzle translation data in Mach table
- Determined to move forward using 3D scan data



Numerical Methods Explored

- Method of Characteristics – solves governing equations along Mach lines within prescribed boundary
 - Classical method for supersonic nozzle design
 - Applies to supersonic regions only
- JUSTUS Code (Euler Module) – general flow field solver
 - Based on the space-time conservation element and solution element method
 - Involves a time-accurate local-time-stepping scheme in the solution time integration (required for nonuniform mesh applications)
 - Uses unstructured meshes

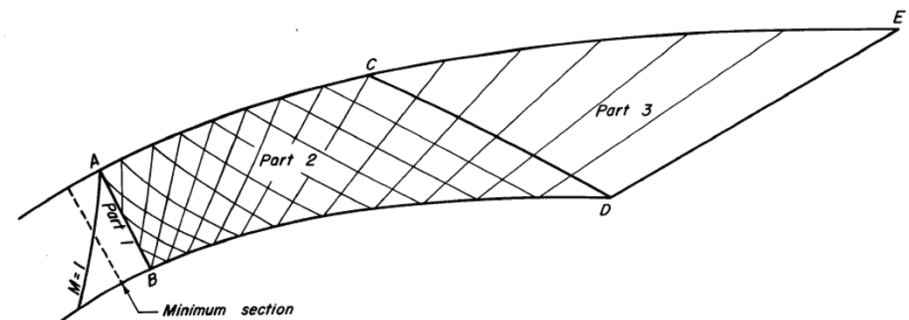


Figure 2.— Schematic diagram of the construction of the flow field in a typical asymmetric nozzle.

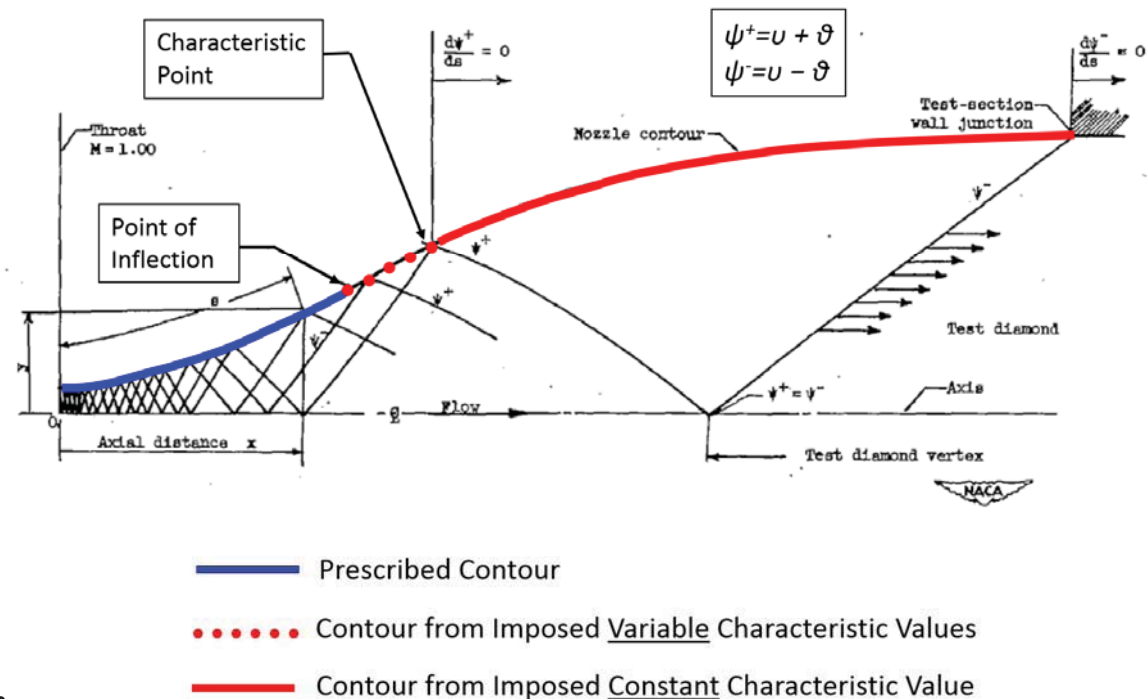


NACA TM 2922

Design Approach 1

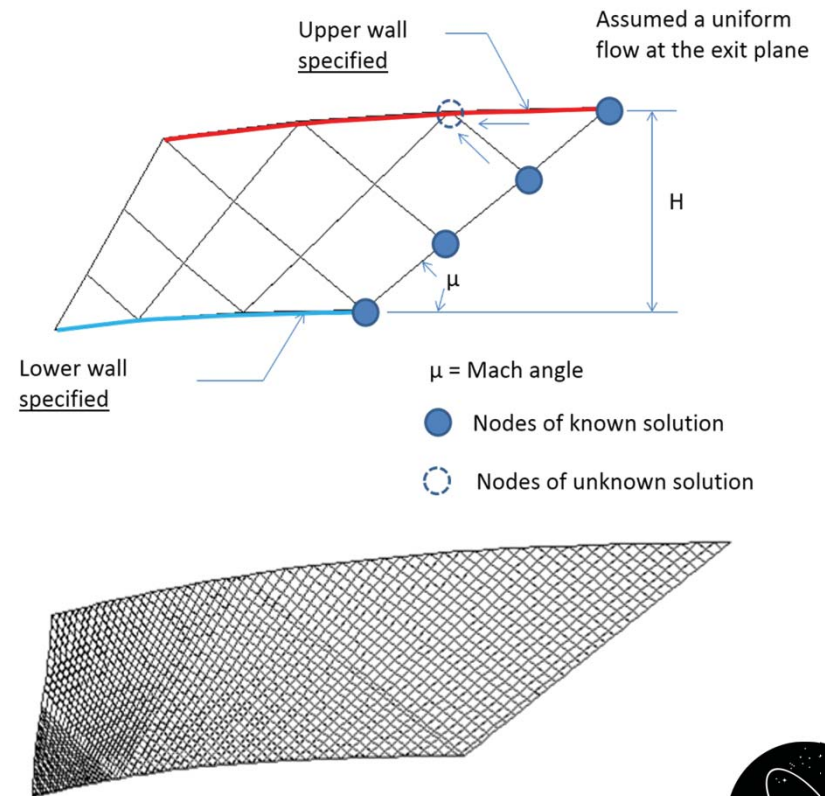
- Evvard & Marcus
 - Scheme:
 - Utilizes MOC framework with additional BC which warrants continuous curvature variation along the nozzle contour
 - Does not rely on partial or full wave cancellation
 - Proven for symmetric nozzles

Reference: Yen J. C., Martindale W. R., "An Inviscid Supersonic Nozzle Design Approach to Perfect Flow Uniformity for Wind Tunnel Applications", AIAA 2008-7059



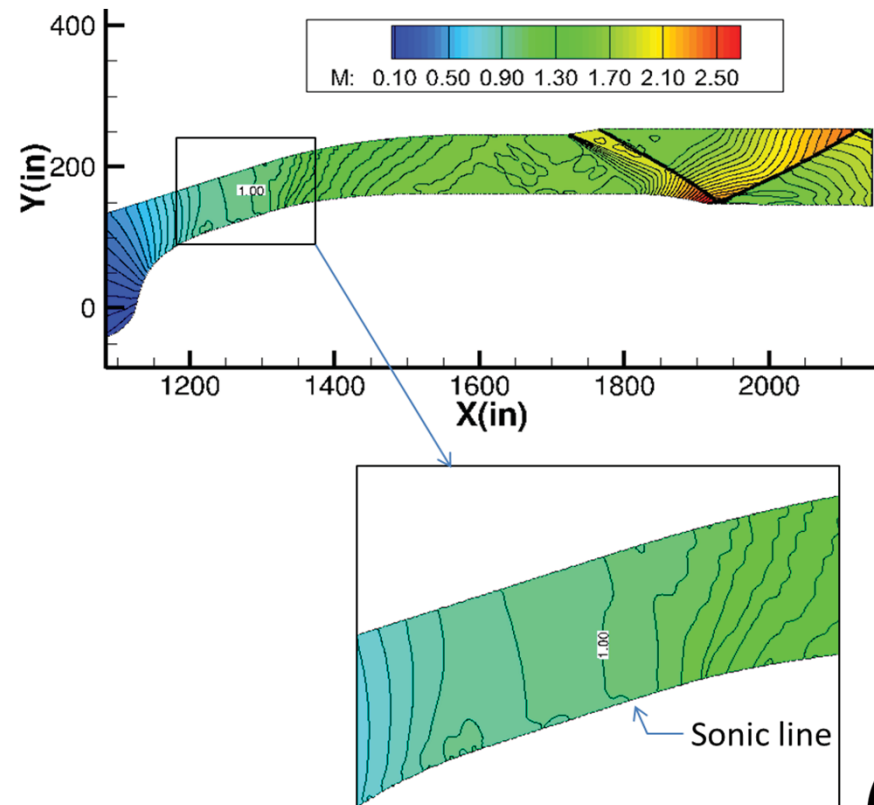
Design Approach 2

- Evvard & Marcus
- Upstream Marching
 - Scheme:
 - Solution propagates upstream from nozzle exit plane along the characteristic line of uniform Mach number
 - Results in a characteristic “net” until the sonic condition is neared
 - Aims for smooth variation with no coalescence of characteristics
 - Lower boundary condition (wall geometry) is changed and next iteration begins
 - Iterative solution



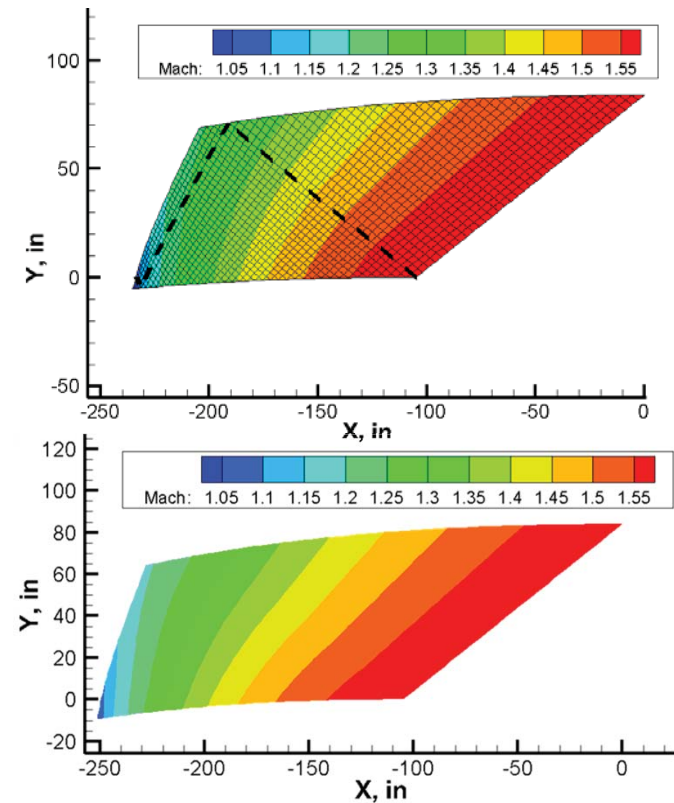
Validation Case

- JUSTUS code (Euler Module) application to the existing curvature
- Performed for Mach setting of 1.6
- Test section Mach distribution showed good agreement with calibration data
- Sonic line curvature suggests room for improvement upstream



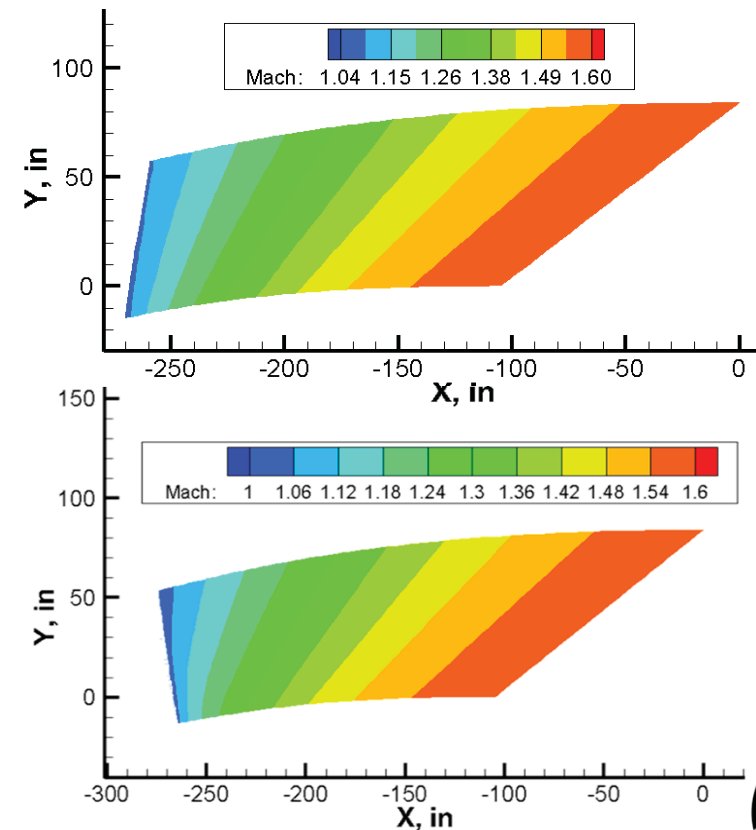
Solutions: Iteration 1 & 2

- Iteration 1: Upper wall curve translated to the lower wall
 - Characteristic lines show an irregularity propagating through the field
 - Mach contours indicate nonuniform flow near the sonic region
- Iteration 2: Interpolated curve between original lower wall and translated upper wall
 - Improved Mach contour continuity
 - Still non-simple Mach number contour near the sonic region



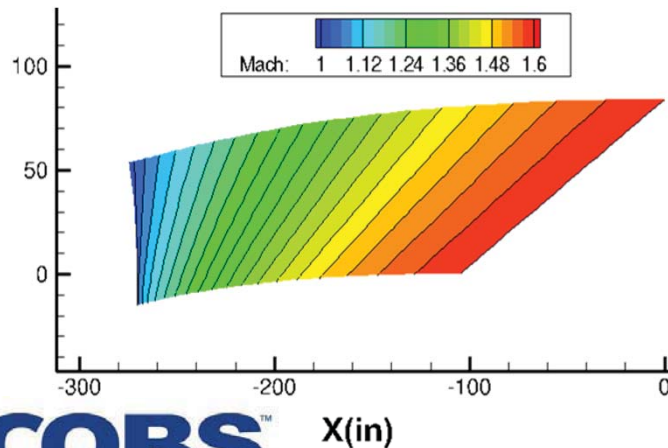
Solutions: Iteration 3 & 4

- Iteration 3: Merged contour from translated upper wall and original lower wall
 - Continuous and smooth Mach number variation – simple wave expansion result
 - Simple contour line near the sonic condition – simple geometry adaptation to the upstream subsonic contracting section
- Iteration 4: Smoothed wall with continuous slope
 - Acceptable Mach number variation
 - Sonic condition reached in close proximity to the test section

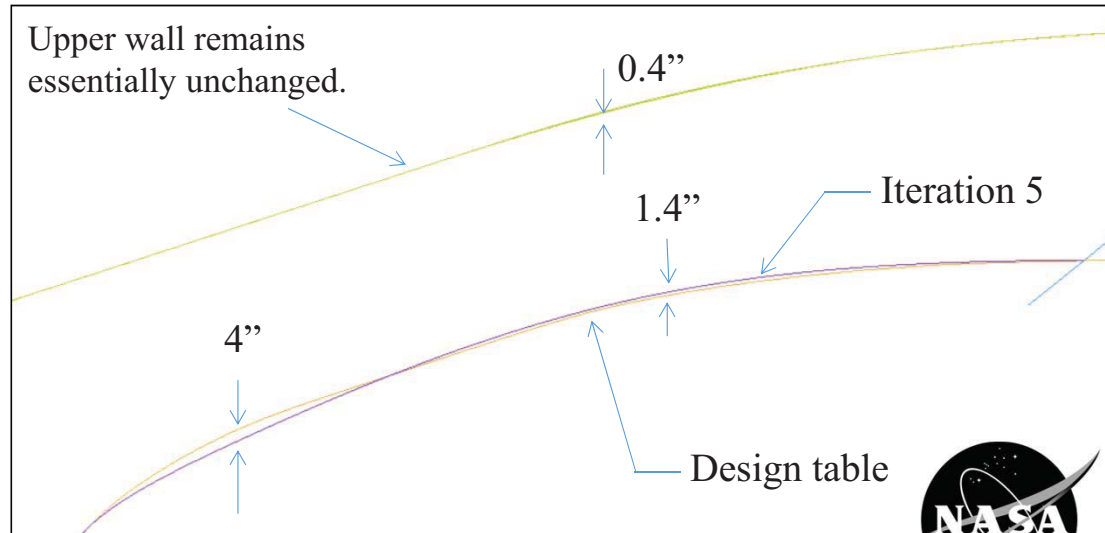
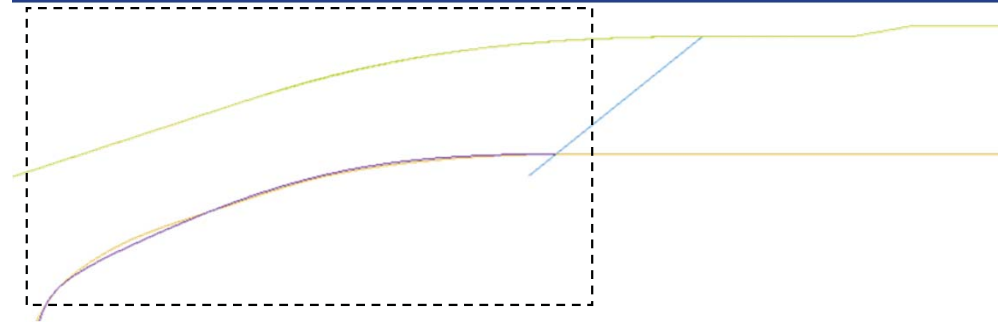


Solutions: Iteration 5

- Iteration 5: Heuristic manipulation of iteration 4 design
 - Uniform characteristic net with no discontinuities
 - Resulting uniform Mach number distribution at the test section
 - Appropriate sonic line location



JACOBS™ X(in)

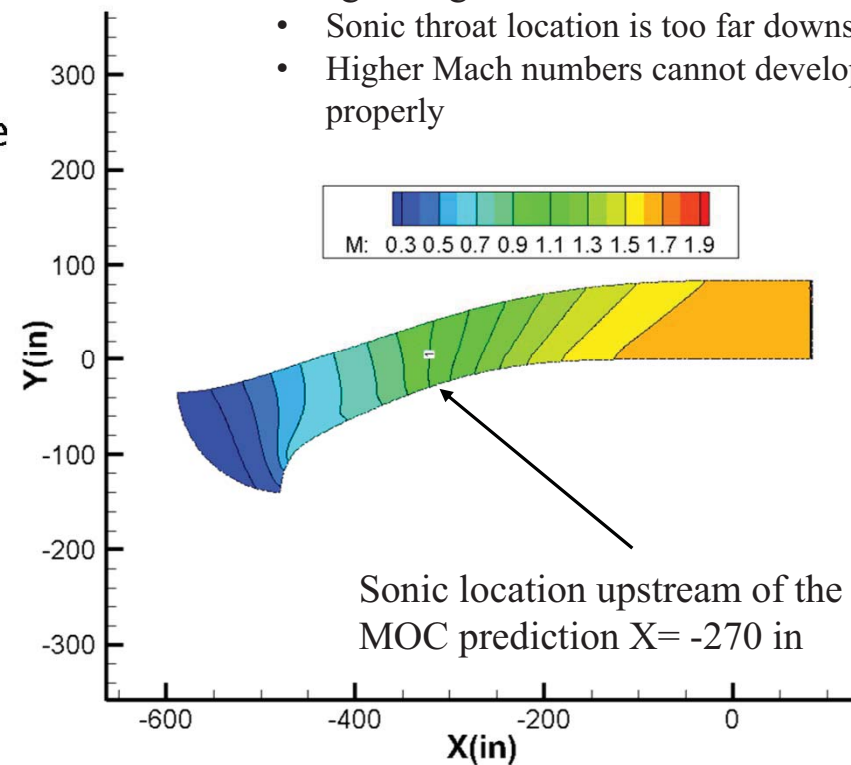


Current Status & Future Direction

- Applying “Iteration 5” curvature throughout Mach number range
 - Preliminary results show flow quality metrics are achievable at 1.3-1.8 range
 - Flow quality at higher Mach numbers improved but does not meet requirements
- Exploring other solutions to improve flow quality in 1.8-2.5 range
- Revisiting flow quality metrics
- Implementing 3D scan geometry

Looking at Higher Mach Numbers

- Sonic throat location is too far downstream
- Higher Mach numbers cannot develop properly



Acknowledgements

JACOBS™



*High Speed
Project*



*Aeronautics
Test Program*

JACOBS™

API SERVICES



Questions?

National Aeronautics and Space Administration



NASA's Aeronautics Test Program

9- by 7-Foot Supersonic Wind Tunnel